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PHOSPHORUS RETENTION OF SHAWNIGAN LAKE WATERSHED SOILS: MANAGEMENT IMPLICATIONS FOR SUBSURFACE DISPOSAL SYSTEMS

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SUMMARY

Phosphorus sorption characteristics of the Shawnigan Lake Watershed soils were studied. Statistically significant linear relationships were found for the amount of phosphorus sorbed with DCB-extractable Fe and silt plus clay content.

In leaching experiments, phosphorus sorption at breakthrough was a function of soil texture and the reaction time. An empirical relationship of the form

$$P_s = a(C + Si)(\frac{nD}{F})^b$$

established phosphorus sorption (P_s) at breakthrough fairly well.

Phosphorus removal efficiency of soils during leaching will improve with slow percolation, decrease in solution nutrient concentration, and intermittent leaching. For a septic tank drainfield to be most effective it was concluded that the following should be used: (a) effluent loading alternated with rest periods, (b) a large seepage area, and (c) a combination of chemical and soil treatment.

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PHOSPHORUS RETENTION OF SHAWNIGAN LAKE WATERSHED SOILS: MANAGEMENT IMPLICATIONS FOR SUBSURFACE DISPOSAL SYSTEMS

INTRODUCTION

Phosphorus is considered to be one of the most important causes of eutrophication of surface waters (Sawyer, 1947; Fuhs et al., 1972; Schindler et al., 1971; Schindler, 1974). Although it is sorbed readily by most soils, land waste-disposal systems such as septic tank drainfields are suspected of contributing significant quantities of phosphorus to lake waters, thus causing adverse effects on water quality (Kalamalka-Wood Lake Basin Study, 1974; Gibbs, 1977). Consequently, unrestricted development of a lake watershed served with septic tank disposal systems is not looked upon favourably. However, septic tank-soil absorption systems are more economical and, if carefully designed and managed, an attractive alternative to centralized sewer systems for communities of relatively low densities. It is therefore essential that phosphorus sorption and movement in soil absorption systems be clearly understood, in order that effects on ground and surface water quality can be minimized through proper design and management.

The sorption of phosphorus by soil materials has been studied extensively (Barrow, 1978; Barrow and Shaw, 1979; Kuo and Lotse, 1974; Gebhardt and Coleman, 1974; Syers et al., 1973; Sain and MacLean, 1965). Several soil and technique-related factors have been recognized to affect measurement of phosphorus sorption; these include amorphous aluminum and iron contents, calcium content, pH, solution concentration, soil : solution ratio, vigour of shaking, and time of contact between soil and solution. Normally, studies conducted over a short reaction time period are used to characterize soils for their phosphorus sorption capacities. More recently, however, attempts have been made to predict phosphorus movement and retention based on long-term phosphorus sorption isotherms (Sawhney, 1977; Tofflemire and Chan, 1977). Sawhney's results indicate that fine sandy loam and silt loam soil columns sorbed approximately the same amount of phosphorus during leaching as was estimated by sorption isotherms. Both leaching and isotherm data were obtained with the same solution, the latter having a reaction time of 200 hours. Isotherms obtained over shorter reaction times may be necessary, however, to predict phosphorus sorption in coarse textured soils leached at high effluent input rates. On the other hand, Tofflemire and Chan (1977) concluded that long-term phosphorus

removal by soils subjected to leaching was two to six times the sorption capacity determined from isotherms obtained over a 120 hour reaction time.

Sorption isotherms used in predicting phosphorus retention and movement during leaching do not take into consideration moisture content and flow conditions within a soil absorption system. This is a serious drawback of these models, since soil moisture conditions affect efficiency of a soil absorption system. It should be recognized, however, that phosphorus sorption is a non-linear function of time and concentration, and phosphorus movement and retention in relation to soil water movement are difficult to quantify (Enfield and Shew, 1975; Novak and Adriano, 1975).

The purpose of this study was to characterize major soils of the Shawnigan Lake Watershed for their phosphorus sorption capacities. This information was sought, in part, for identifying potentially unsuitable soils for septic tank drainfields. Attempts were also made to develop an empirical relationship that would estimate phosphorus retention and movement, based on soil properties and soil water flow conditions.

MATERIALS AND METHODS

Soils sampled for this study, their physical and chemical characteristics, and their location in the watershed, are listed in Table 1. These soils were also analysed for their phosphorus sorption capacities under both equilibrium (shaking with a known phosphorus solution) and steady-state (leaching with a known phosphorus solution) conditions. The procedures used are described below.

1. PHOSPHORUS SORPTION - SHAKING EXPERIMENTS

A. Short-term Sorption

One gram of the less than 2 mm size fraction of each soil, was added to a test tube containing 10 ml of 10 mg/L-P solution prepared from KH_2PO_4 crystals. The mixture was shaken for about one minute every twenty minutes. At the end of 30 minutes the mixture was centrifuged at 1800 RPM for 10 minutes, and the solution at the top was decanted and analysed for soluble P (McKeague, 1976). Based upon initial and final solution concentrations, phosphorus sorption by the soil was computed. The results are shown in Table 1.

B. Long-term Sorption

In this series of experiments, 15 g of soil < 2 mm in size was added to a 500 ml capacity widemouthed plastic bottle containing 300 ml of 10 mg/L-phosphorus solution. Three soils and eight reaction times were used. The bottles containing the soil-solution mixture were capped tightly and placed lengthwise on a shaker tray. The mixture was shaken continuously at a rate of 82 cycles per minute for periods of 0.5, 4, 8, 24, 48, 96, 168 and 192 hours. At the end of each period, the contents of the bottle were filtered under pressure, through a 0.45 micron sartorius membrane filter. A blank was also run to correct for sorption of phosphorus by the filter, if any. The filtrate was analysed for orthophosphorus concentration (McQuaker, 1976).

C. Phosphorus Sorption Isotherms

The procedures followed to obtain sorption isotherms were the same as outlined in section (B). The same three soils, and phosphate solutions containing 2, 4, 6, 10, 20 and 40 mg/L-phosphorus, were used. The soil-solution mixture was shaken continuously for a period of 30 minutes and the filtrate was analysed for its phosphorus content.

2. PHOSPHORUS SORPTION - LEACHING COLUMNS

The leaching columns were prepared using commercially available plastic buchner funnels, 10 cm in diameter. In order to prevent soil from sifting through the holes, the perforated bottom of the funnel was lined with nylon cloth. A known weight of air-dry soil was placed in the funnel and tapped to allow the soil to settle.

The soil was leached with 10 mg/L-phosphorus solution. During the leaching, flow through the soil was maintained at a constant rate, by holding the water level at the soil surface with a mariotte device. Both volume and concentration of the leachate were measured periodically. A minimum of 250 ml of the leachate was collected for orthophosphorus analysis.

RESULTS

1. Phosphorus Sorption Versus Soil Properties

The short-term phosphorus sorption results and data for selected soil properties of the Shawnigan Lake Watershed soils are shown in Tables 1 and 2. These results

indicate a fairly good linear relationship between Dithionite-Citrate-Biocarbonate (DCB) extractable Fe content and phosphorus sorbed (significant at 5% level). This agrees with the results of Juo and Fox (1977) and Syers et al. (1971).

Although acid ammonium oxalate (AAO) extractable iron content has been considered the best criterion for explaining phosphorus sorption in non-calcareous soils (Shukla et al., 1971; Khalid et al., 1977; Syers et al., 1971), the relationship between AAO extractable Fe and phosphorus sorbed was found insignificant for soils used in this study (Table 2). The reason for the discrepancy is not clearly understood. However, two plausible reasons can be mentioned based on available literature. First of all, the variability in phosphorus sorption with respect to AAO-extractable iron is so great, that the data base in Table 1 is not large enough to perform a meaningful regression analysis. Secondly AAO-extractable Fe (Table 2) falls into the range which has been shown not to have a positive correlation with phosphorus sorbed. The Khalid et al. study suggests a non-significant correlation for phosphorus sorbed at AAO-extractable Fe contents of >0.40%. For the Shawnigan Lake Watershed soils, AAO-extractable Fe ranged from 0.56 to 0.92% (Table 2).

The results in Table 2 also show a fairly good correlation (r=0.691) between phosphorus sorbed and silt plus clay content. This positive correlation has been attributed, in the literature (Rea and Upchurch, 1980; Williams et al., 1958), to sodium pyrophosphate (SPP) extractable Fe content associated with the organic fraction of the soils, which in turn correlates significantly with the (silt + clay) fraction. Although the data in Table 2 suggest a definite relationship among (silt + clay), carbon, and SPP-extractable Fe contents, no correlation was found between phosphorus sorbed and SPP-extractable Fe content.

2. Phosphorus Sorption Isotherms

Phosphorus sorption isotherms for Rosewall, Qualicum, and Shawnigan soils are shown in Figure 1. Although the amount of phosphorus sorbed by the soils increased with increase in solution concentration, percent sorption of added phosphorus decreased for all three soils. Implications of the relationship in the operation of a soil absorption system are discussed in a later section.

TABLE 1

Physical and Chemical Characteristics of Shawnigan Lake Watershed Soils

Soil Series	Location Sampled	Phosphorus Sorbed	Silt & Clay	Fe			Al		
				SPP*	AAO**	DCB***	SPP*	AAO**	DCB***
		mg/100 g	%	%			%		
Robertson (Bm)	Carter Rd	8.88	50.7	0.25	0.67	1.39	0.36	0.74	0.64
Qualicum (Bm_2)	Gravel Pit	9.65	43.2	0.18	0.88	1.58	0.32	0.88	0.75
Chemainus (Bm)	Cliffside School	9.90	77.7	0.74	0.92	1.98	0.75	1.50	1.17
Shawnigan (Bm_3)	Worthington Rd.	8.00	34.9	0.15	0.71	1.01	0.32	0.91	0.66
Shawnigan (Bm_1)	Knappet Rd.	9.40	60.3	0.21	0.62	1.31	0.29	0.61	0.49
Shawnigan (Bm_3)	Prov. Park	9.21	42.5	0.20	0.54	1.31	0.34	0.76	0.69
Shawnigan (Bm)	Mason's Store	9.65	52.0	0.15	0.70	1.49	0.36	0.92	0.69
Robertson (Bm)	Haybrook Rd.	9.32	47.7	0.16	0.56	1.28	0.37	0.89	0.78
Esquimalt (Bm)	Shawnigan Cr.	9.75	75.7	0.59	0.65	1.36	0.50	0.77	0.75

* Sodium Pyrophosphate Method
** Acid Ammonium Oxalate Method
*** Dithionite-Citrate-Bicarbonate Method

TABLE 2

Regression Equations and Correlation Coefficients Between Various Physical and Chemical Properties of Shawnigan Lake Watershed Soils

		Silt + Clay (%)	Fe (%)			Al (%)		
			SPP	AAO	DCB	SPP	AAO	DCB
Phosphorus Sorbed (%)	y=	7.84 + 0.027x			6.96 + 1.66x			
	r=	0.691*	0.510^{NS}	0.285^{NS}	0.759*	0.491^{NS}	0.291^{NS}	0.432^{NS}
SPP-Al (%)	y=		0.22 + 0.62x					
	r=		0.933**					
AAO-Al (%)	y=			-0.07 + 1.37x				
	r=			0.711*				
DCB-Al (%)	y=				-0.02 + 0.54x			
	r=				0.782**			
(Silt + Clay)	y=		36.2 + 60.5x			21.6 + 80.3x		
	r=		0.890**	0.280^{NS}	0.624^{NS}	0.782**	0.396^{NS}	0.507^{NS}
Carbon	y=	-1.90 + 0.076x						
	r=	0.824**						

*, ** Significant at 5% and 1% levels respectively.
NS Not significant at 5% level.

3. Long-Term Phosphorus Sorption Characteristics

Figure 2 shows phosphorus sorption characteristics for longer reaction periods. These curves were obtained with a solution containing 10 mg/L phosphorus. The results indicate a rapid sorption of phosphorus during the early stage of reaction with the soils. This was followed by a relatively slow rate of phosphorus sorption. A regressional analysis performed on the transformed data showed that phosphorus sorption was a power function of reaction time (Table 3). Though still significant, the correlation coefficient was the poorest for the Rosewall series. This may be attributed to the relatively high sorption capacity of the soil in relation to the amount of phosphorus added. From Figure 2 it can be readily seen that almost all of the added phosphorus was sorbed by the soil within one-eighth (25 hours) of the total reaction time of 192 hours used for this experiment.

Table 3 also shows results of the regressional analysis performed on data presented in Figure 1. These results clearly indicate that for a specific soil type, phosphorus sorption is dependent upon both solution concentration and reaction time. Also, it can be shown that phosphorus sorption is more sensitive to change in solution concentration than in time of reacton. For instance, in the case of the Qualicum soil, an order of magnitude increase in solution concentration increased phosphorus sorption by 4.84 times, whereas a similar change in reaction time would cause an increase in sorption of 1.42 times only. However, in a real situation of a septic tank drainfield system,

TABLE 3

Regressional Analyses For Long-Term Sorption and Phosphorus Sorption Isotherms

Soil	Phosphorus Sorption Characteristic (y)			
	Sorption vs Time		Sorption vs Concentration	
	Regression Eqn.	r	Regression Eqn.	r
Qualicum	$7.25\ T^{0.1519}$	0.989**	$0.96\ C^{0.685}$	0.985**
Shawnigan	$9.96\ T^{0.1187}$	0.992**	$1.47\ C^{0.602}$	0.961**
Rosewall	$15.12\ T^{0.0564}$	0.929**	$2.39\ C^{0.704}$	0.997**

T Time of reaction (hr).
C Solution concentration (mg).
y Phosphorus sorbed (mg/100 g).
** Significant at 1% level.

nutrient (phosphorus) characteristics of the effluent may vary at a site by relatively small amounts (3 to 4 times), whereas water flow conditions, hence reaction times, may differ by more than 100-fold, depending upon hydrologic conditions (i.e., clogging) and properties of soils (Kreissl, 1978). This would make reaction times and/or flow rate factors as important as effluent concentration in determining nutrient renovation ability of a soil absorption system.

4. Phosphorus Sorption - Leaching Columns

The ratio of C/C_o as a function of pore volume leached through soil columns is shown in Figures 3 through 5. The values C and C_o are the outflow and inflow phosphorus concentrations, in mg/l, respectively. A relatively high C/C_o ratio for the second and third runs of Rosewall and Qualicum soils respectively, at the beginning of the experiments, imply that the breakthrough of phosphorus occurred immediately after leaching was initiated (Figures 3 and 4). However this unexpectedly early apparent breakthrough was attributed to unrestricted, rapid movement of the effluent along the outer edges of the columns as a result of poor contact between the soil and the column (buchner funnel) wall. A close analysis, in fact, showed that effluent flow rates were much higher at the beginning of the experiments than the average values indicated in Table 4.

Results in Figures 3, 4, and 5 show a sudden dip in the C/C_o ratio during the course of the leaching experiments. This decrease in C/C_o ratio occurred following a nocturnal rest period during which time leaching was terminated temporarily by clamping the outlet of the leaching columns, while a constant P-solution level was maintained at the soil surface. Sorption of phosphorus by the soil, however, continued during the rest period. As a result, a decrease in C/C_o was observed when leaching was resumed the next day. These results also indicate that recovery in C/C_o was rapid and nearly complete upon resumption of leaching. The recovery in the C/C_o ratio appeared to be a function of (a) magnitude of C/C_o decrease which, in turn, depends upon length of rest period, (b) soil type, (c) effluent flow characteristics, and (d) position on the breakthrough curve. It can be concluded that intermittent loading will enhance overall nutrient (phosphorus) removal efficiency of a soil column. Regeneration of phosphorus sorption sites in septic tank drainfield systems with time was also observed by Sawhney and Hill (1975). Implications of these results in relation to a drainfield operation are further discussed in a later section.

In order to determine phosphorus loading to ground and/or surface waters from waste disposal systems, it is necessary that phosphorus sorption characteristics of the soil in question be clearly defined under field conditions. Recently, long-term phosphorus sorption characteristics, as in Figure 2, have been used to predict phosphorus movement (Sawhney, 1977; Tofflemire and Chen, 1977). As these determinations are easy to make, this approach is an attractive one, the major disadvantage being the fact that it does not consider effluent flow characteristics in the soil. The importance of flow rates and/or time of reaction has been pointed out earlier. In view of this, attempts were made to express phosphorus sorption capacity on the basis of flow rate.

Table 4 shows the results of the leaching experiments. In these experiments breakthrough was defined to occur when 10% of incoming phosphorus leaches though, i.e., $C/C_o = 0.10$. In earlier discussion, it was shown that phosphorus sorption by soils could be expressed as linear and power functions of the (silt + clay) fraction (Table 2) and reaction time (Table 3) respectively. To predict phosphorus movement in leaching columns, therefore, an empirical relationship of the form

$$P_s = a(C + Si)\ \left(\frac{nD}{F}\right)^b \qquad (1)$$

was used. In equation (1) P_s refers to phosphorus sorption (mg/100 g) at breakthrough, (C + Si) is the clay plus silt fraction of the soil, n is fractional soil porosity, D is distance (cm) through which effluent travels or length of soil column, and F is apparent effluent flow rate (cm/day) through the soil. The quantities 'a' and 'b' are the constants. The ratio $\frac{nD}{F}$ is an indicator of reaction time between solution and the solid phase.

In order to use relation (1), values for the constants 'a' and 'b' must be known. Because of limited amounts of data, 'a' and 'b' could not be determined statistically. Instead, the data obtained with Qualicum soil, runs #1 and 2, were used to determine these constants (Table 4). The final result of these calculations is shown below.

$$P_s = 279.8\ (C + Si)\ \left(\frac{nD}{F}\right)^{0.614} \qquad (2)$$

Equation (2) was then used to predict phosphorus sorbed for Qualicum (Run #3), Shawnigan, and Rosewall leaching columns. The measured P_s for these soils are also shown in Table 4.

TABLE 4

Phosphorus Sorption at Breakthrough During Leaching Experiments

Soil	Length of Soil Column (D)	Porosity (n)	Av. Flow Rate (F)	Clay + Silt	C/C_o at B.T.*	P.V.** at B.T.*	Phosphorus Sorbed (P_s)	
							Measured	Predicted
	cm		cm/day				mg/100g	
Qualicum #1	2.1	0.453	138	0.35	0.10	15.5	4.61	-
#2	2.1	0.408	535	0.35	0.10	7.5	1.88	-
#3	2.4	0.473	328	0.35	0.10	1.5	1.38	3.02
Shawnigan	2.9	0.492	154	0.60	0.10	32.0	11.29	9.48
Rosewall #1	4.3	0.658	311	0.85	0.10	29.0	13.82	13.26
#2	3.7	0.659	239	0.85	0.10	9.5	6.57	14.24

*B.T. Breakthrough
**P.V. Pore Volume

The predicted and measured P_s values agreed well for the Shawnigan and Rosewall (Run #1) soils. The maximum error was found to be -16.0% of the measured P_s. In the cases of Qualicum (Run #3) and Rosewall (Run #2), however, little agreement was observed between measured and predicted P_s. This discrepancy was attributed to error in the breakthrough characteristics (Figure 3 and 4). It was shown that for these experiments poor contact between the soil and the column wall resulted in an unexpected early breakthrough of phosphorus. One would, therefore, expect measured P_s to be smaller than what it should have been. A comparison with predicted P_s (Table 1) for these cases appears to support this observation.

Although equation (2) adequately predicted phosphorus sorption in this study, the data used to arrive at this empirical relationship was limited. Also, the flow rates used in this study were generally much higher than those found normally under a soil absorption system. It is therefore necessary that usefulness of this relationship be tested on a wide variety of soils and water flow conditions.

5. Management Implications

Soil absorption systems are the most economical alternative to centralized sewer systems for domestic waste disposal in low population density communities. As these systems are possible contributors of nutrient loading to ground and surface waters, proper design and management of drainfields is extremely important if downstream eutrophic-type impacts are to be avoided.

A continuously or frequently loaded drainfield will exhaust its apparent nutrient (phosphorus) retention capacity rather quickly. On the other hand, the apparent nutrient sorption capability of a drainfield will increase if frequency of hydraulic loading is decreased. No more than a single dose per day has been recommended for medium (sandy loam to loam) to fine (silt loam to clay) textured soils (Bouma, 1975). The effectiveness of the soil system will be further enhanced if the practice of single daily loading is followed right from the beginning.

Rate of wastewater flow through soil is another factor that determines effectiveness of a drainfield system. A system installed in a highly permeable sandy soil will be less effective in removing phosphorus from wastewater than a slowly permeable clay soil. Given hydraulic loadings, distributed over a larger area will, however, effectively reduce effluent flow rate through a sandy soil. Wide trenches or even seepage

beds with larger percolating area, and/or numerous short, closely spaced trenches will increase the effectiveness of a coarse textured sandy soil by effectively reducing effluent flow rate.

Nutrient removal efficiency of a soil absorption system is much higher if nutrient loading and/or nutrient concentration in wastewater is lower. In critical areas one may find that controlling wastewater nutrient concentration at the source may be the only alternative for efficient operation of a soil absorption system. In such situations, a combination of chemical treatment with alum, lime, or ferric chloride in the septic tank (Cooper, 1975; Brandes, 1977), or soil (drainfield) treatment, will achieve high phosphorus removal.

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FIGURE 1. PHOSPHORUS SORPTION CHARACTERISTICS FOR THREE SOILS USED IN LEACHING STUDIES.

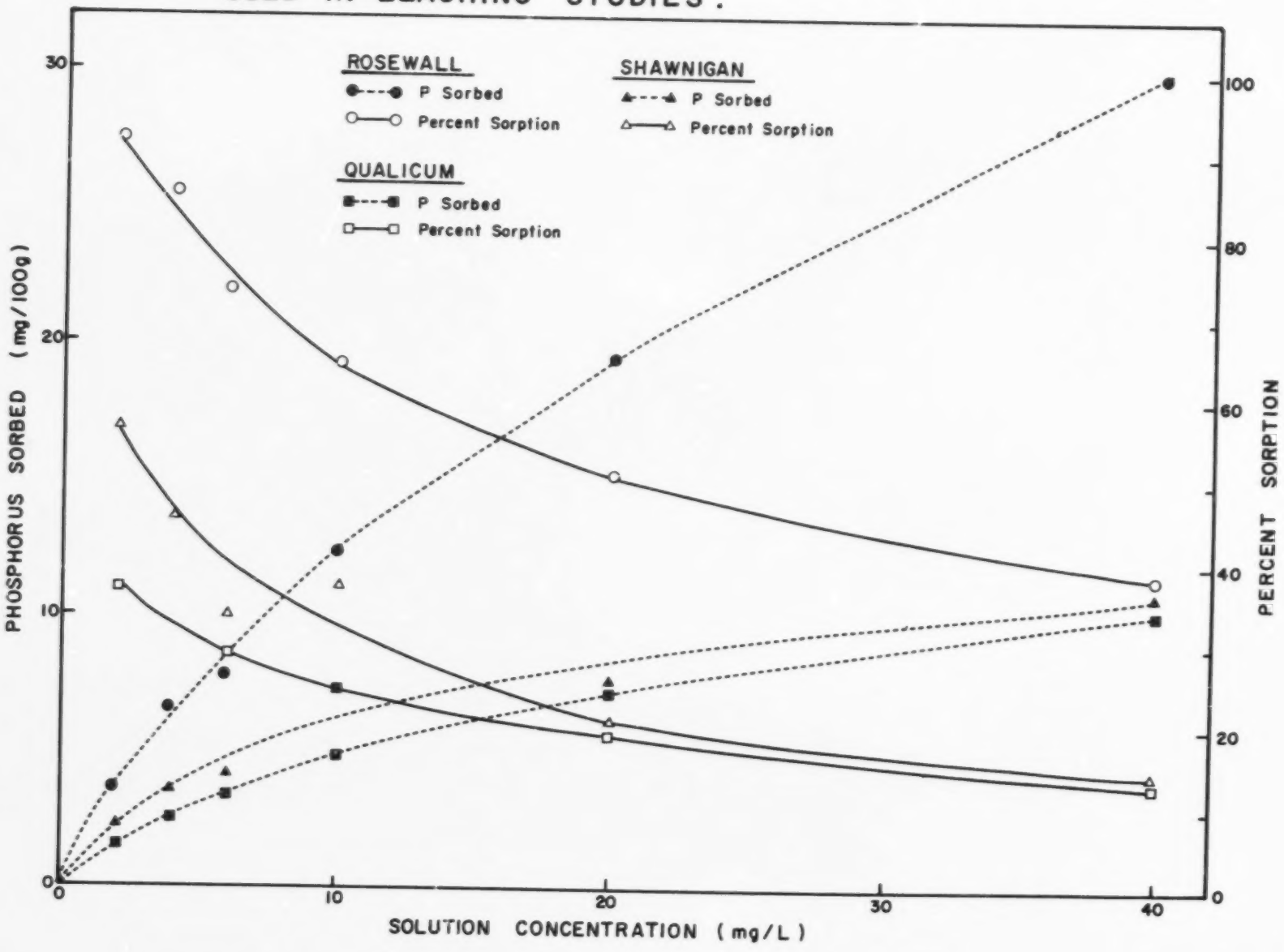


FIGURE 2. ORTHOPHOSPHATE PHOSPHORUS SORPTION BY THREE SOILS SHAKEN FOR VARYING TIMES IN A 10 mg/L – P SOLUTION.

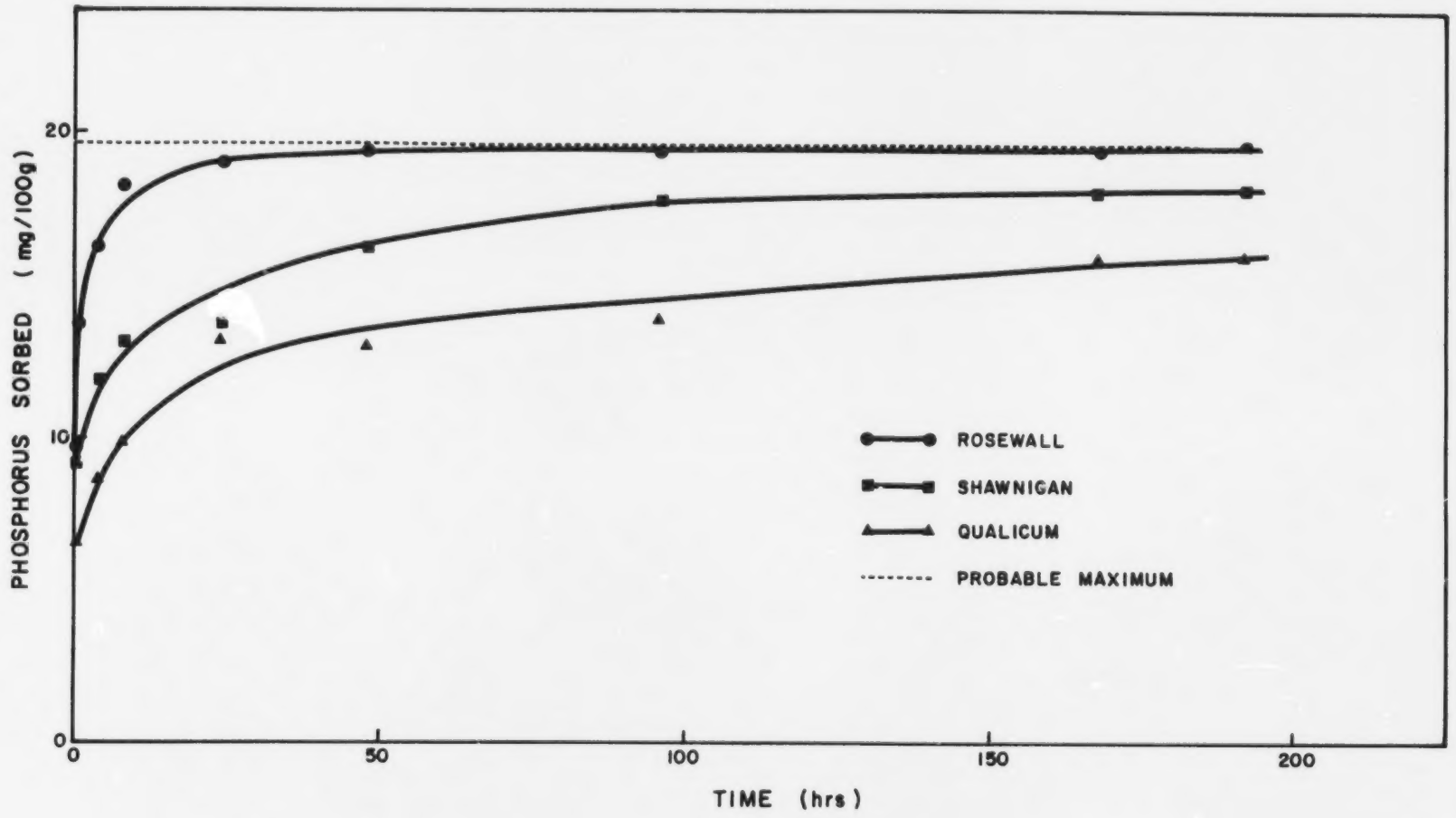


FIGURE 3 . RELATIVE PHOSPHORUS CONCENTRATION (C/Co) AS A FUNCTION OF PORE VOLUME . INFLUENT P CONCENTRATION WAS 10 mg / L .

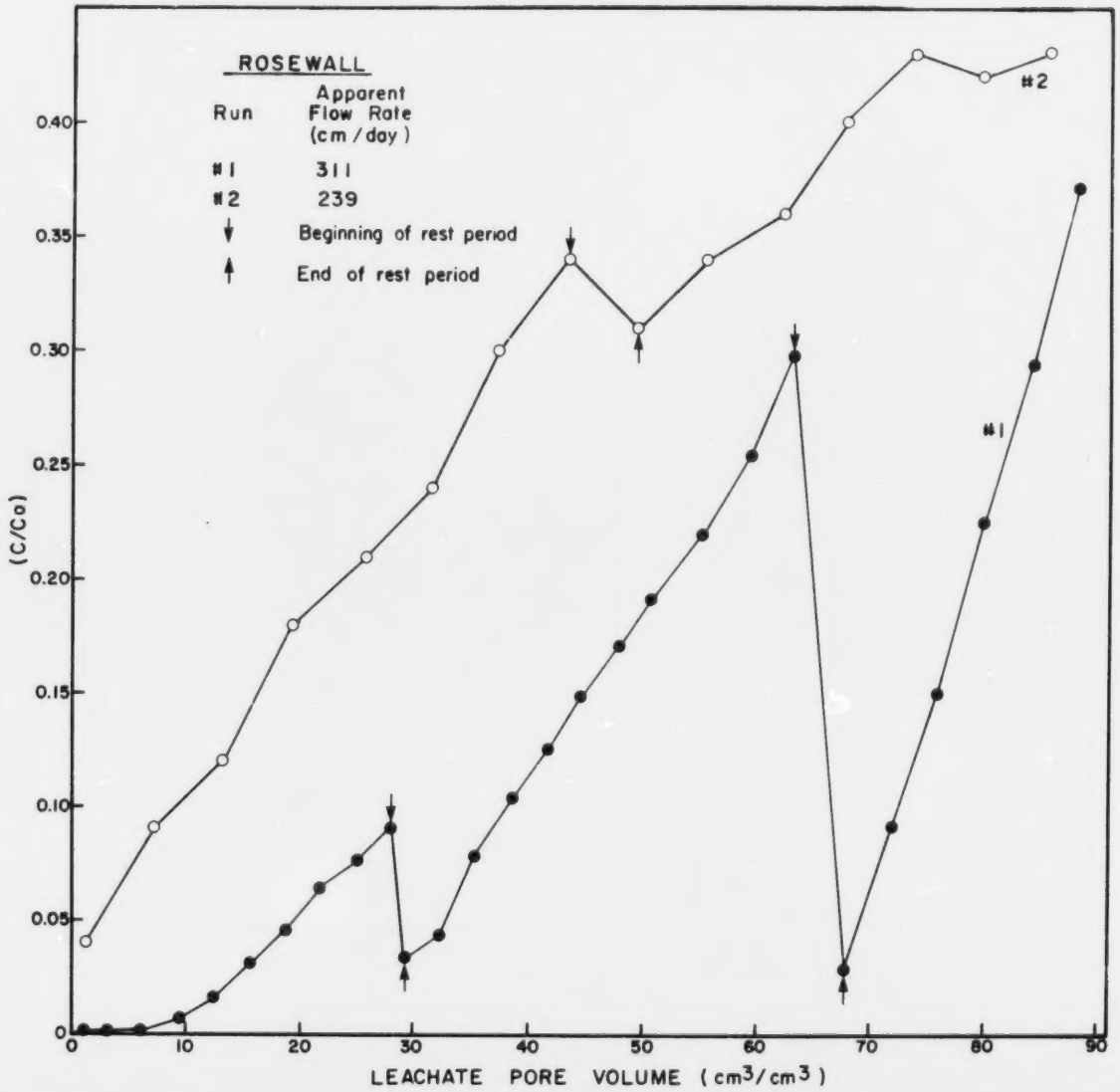


FIGURE 4 . RELATIVE PHOSPHORUS CONCENTRATION (C/Co) AS A FUNCTION OF PORE VOLUME. INFLUENT P CONCENTRATION WAS 10 mg/L .

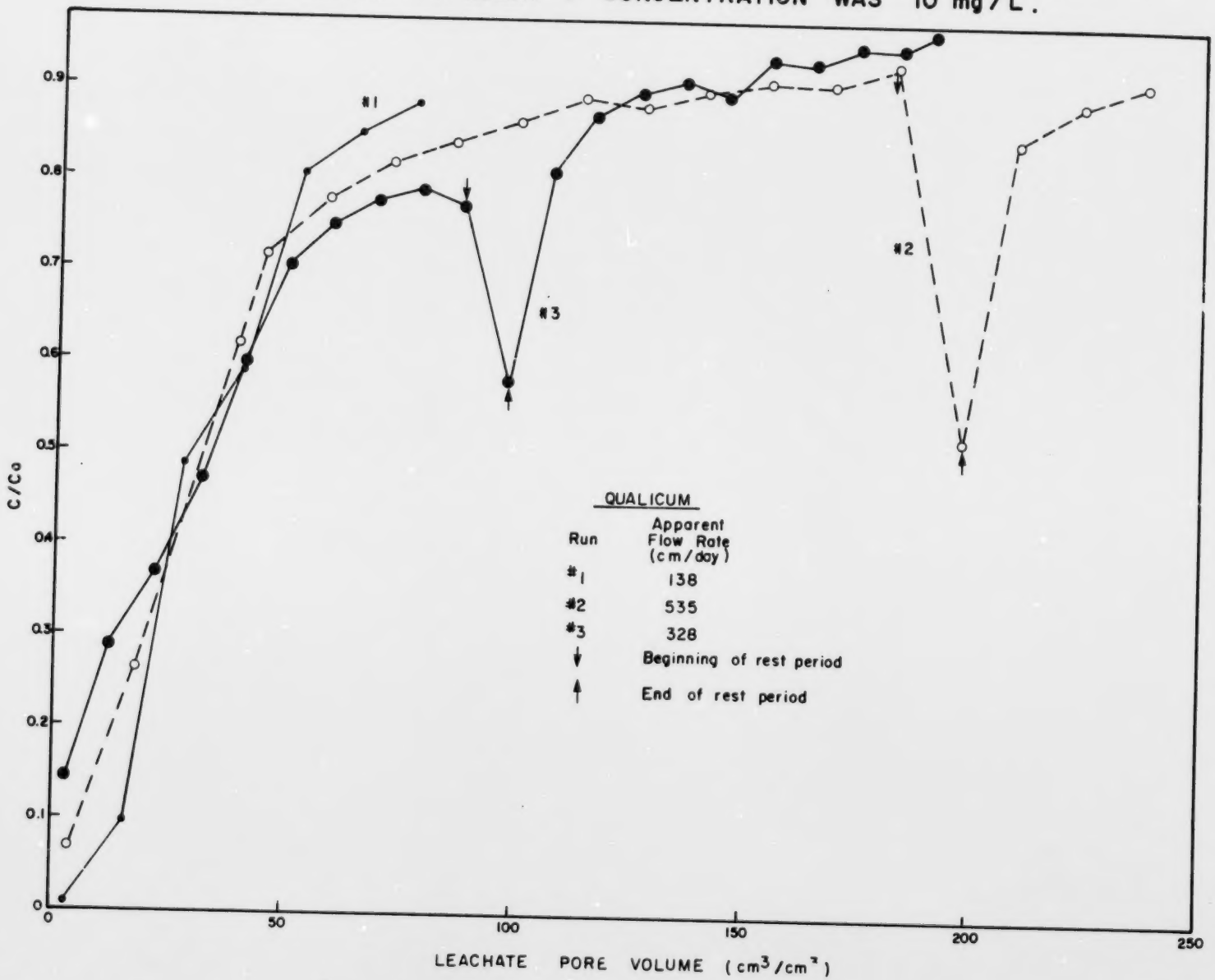
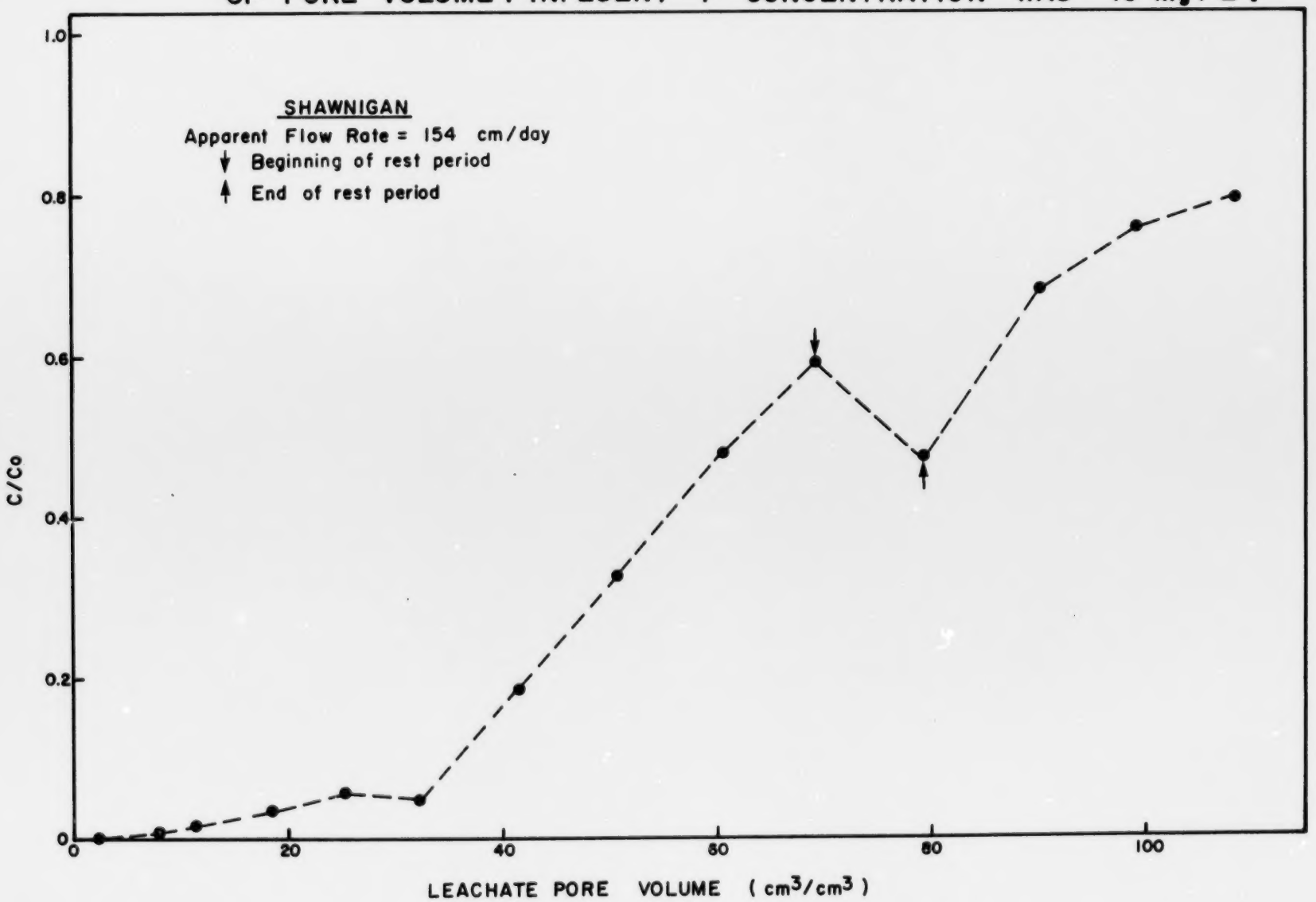


FIGURE 5 . RELATIVE PHOSPHORUS CONCENTRATION (C/Co) AS A FUNCTION OF PORE VOLUME . INFLUENT P CONCENTRATION WAS 10 mg/L .



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